Structures Laboratory

The Structures Laboratory advances the national defense and civil engineering capabilities of the nation in the fields of weapons effects, structural dynamics, construction materials, and structural design.

The Structures Laboratory is the preeminent R&D organization conducting research related to force protection and is the lead Department of Defense laboratory for Survivability and Protective Structures under the Defense Science and Technology Reliance Program. These studies yield results that not only help form the technical database for defense planning and acquisition but also address specific and immediate problems as they arise.

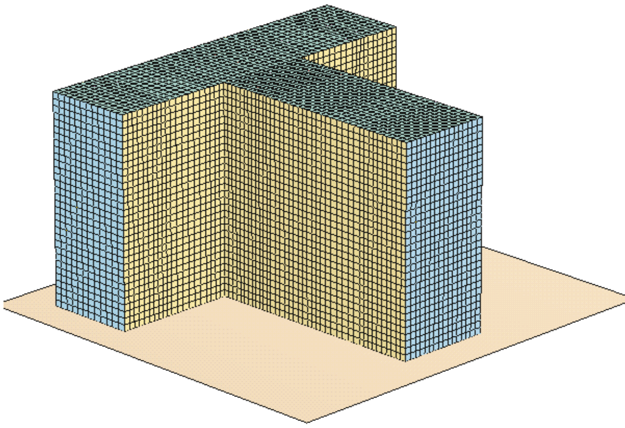
The Structures Laboratory is the principal Corps R&D agency for concrete and structural engineering research. This research involves theoretical, analytical, and experimental methods. Research is also performed to predict the response of large structures to the dynamic forces of an earthquake. Construction materials research involves extensive studies of materials, methods, proportioning, manufacturing, placing, curing, and related factors.

High-Performance Computing in Computational Structural Mechanics. The Structures Laboratory conducts research in numerical modeling and develops computational structural mechanics techniques for high-performance computing. To validate numerical models and to enhance understanding of the phenomenology of structural response under various dynamic loading conditions, WES validates the results of its numerical simulations by comparison with those of field and laboratory experiments. In FY 97, computational structural mechanics research projects included the technology areas of scalable computing, weapons effects, material modeling, structural dynamics, and structure-medium interaction.

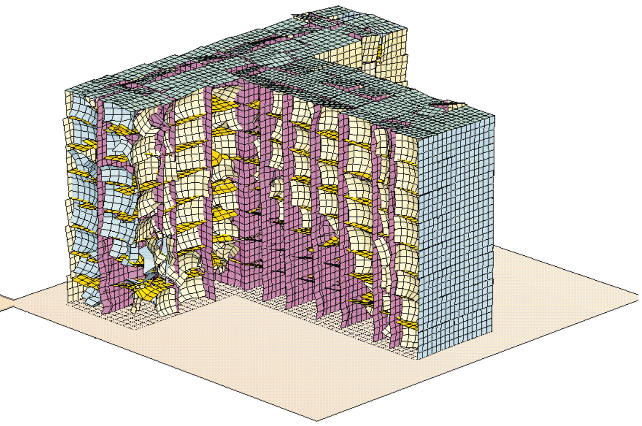
After the June 1996 terrorist bombing attack at the Khobar Towers complex, numerical simulations of various scenarios of the truck-bomb explosion and building damage were conducted on high-performance computers with multiple processors to assist the Department of Defense in evaluating the bomb yield. The terrorist truck-bomb explosion simulation involves modeling of high-explosive initiation, detonation, truck destruction, fragmentation, and blast-wave propagation.

To model these phenomena, 3-D simulation requires solving millions of nonlinear equations. Computational structural mechanics software, CTH (an Eulerian-based finite-volume software developed by Sandia National Laboratories), along with constitutive model fits developed at WES based on material-property experiments were used to perform the simulations. For a 15-millisecond simulation time, the calculations required 450 Central Processor Unit hours, 600 Mwords of memory, and 16 processors on a C-90 supercomputer. These numerical simulations provided the wealth of information necessary to understand asymmetry of the blast pressures and the effects of the cylindrical explosive charge. The numerical simulations and the results of large-scale experiments were in excellent agreement.

Numerical simulations of damage to one of the buildings of the Khobar Towers complex subjected to airblast due to an alternative terrorist bomb explosion scenario were also performed. This scenario assumed that the truck was positioned within the compound as opposed to the truck's actual location. Based on numerical simulations, it was determined that the building would have collapsed, leading to a greater loss of life and grave injuries. Simulations were performed on a C-90 vector computer using DYNA3D software (a Lagrangian-based finite-element software developed at Lawrence Livermore National



Finite element model



Damaged structure at 230 ms

Numerical simulation of alternate scenario with the truck bomb inside the Khobar Towers compound

Laboratory). Concrete material models used in the analysis were extensively validated with experiments.

Two proposals submitted by the Structures Laboratory were selected as Department of Defense High-Performance Computing Challenge Projects. Evaluation criteria for these proposals are based on technical merit, relevance, scalable computing technology, and significant computational requirement. Seventeen proposals were selected out of 67 submitted by various Department of Defense organizations and academia. Compared to other projects, significant computing resources were allocated for the two WES projects. Large-scale simulations of practical problems, validation of simulations with experiments, and Department of Defense High-Performance Computing Challenge Project awards demonstrate WES's technological advancement in the area of high-performance computing in computational structural mechanics.

Full-Scale Building Explosive Experiments. In October 1996, WES led a team of U.S. agencies in participation with the Israeli Home Front Command on a series of high-explosive experiments on a full-scale, five-story building at a site in Israel. Nine experiments were conducted with various high-explosive charges to gather data on the blast response of the building as a whole and on the response of various masonry wall panels and windows. Over 100 channels of instrumentation recorded blast pressures, accelerations, and strains for each of the nine experiments.

The design of reinforced concrete "protected space" towers was evaluated for protection of building occupants from blast effects. Many of the building's walls and windows were retrofitted, and the retrofits were evaluated for their effectiveness in reducing debris hazards. One of the more impressive retrofits was a geotextile fabric that was anchored to the floor slabs to catch masonry wall debris. This concept was able to reduce the hazard inside the building at blast levels three to four times those that would fail an unretrofitted masonry wall.

Blast experiment on full-scale, five-story building

Fragment Environment from Conventional Weapons. A conventional weapon detonating inside a facility will not only damage the room in which it detonates, but fragments from the weapon may penetrate floors and walls and produce damage to equipment, tanks, piping, munitions, or personnel in adjacent rooms. The degree of damage depends on the mass and velocity of the fragments. Research is providing data on the residual velocity of bomb-casing fragments after they have passed through walls of various types and thicknesses representative of soft targets. Multiple-fragment experiments were conducted using scale-model fragmenting weapons. An analytical procedure was developed to predict residual velocities, and the data from the experiments are being used to validate and improve the model.

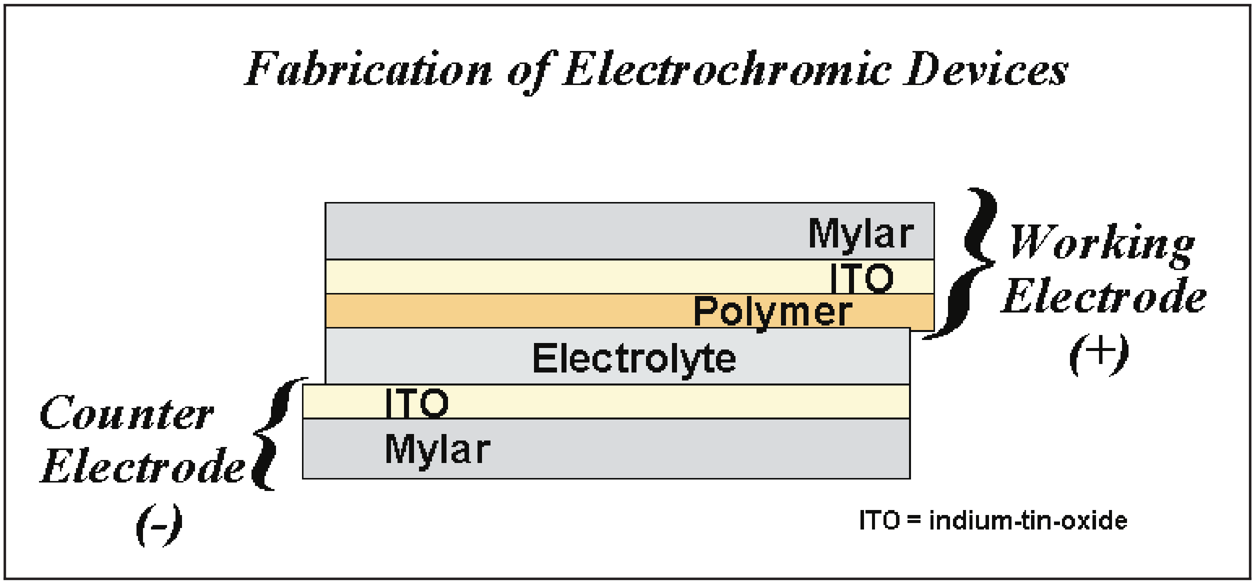
In addition to research on fragment effects on soft targets, research is also addressing the fragment impact effects on hardened structures. This effort is investigating the impulsive loading transmitted to reinforced-concrete slabs from impacting bomb fragments. This loading is affected by the areal density of the fragment pattern, as well as the mass and velocity of front-face crater ejecta and backface spall. An array of several fragments were explosively propelled into concrete slabs suspended in a pendulum configuration. Conservation of momentum and conservation of energy of the pendulum system can be used to determine the impulse delivered to the slab in each experiment. These data will be used to develop fast-running PC-based algorithms for predicting structural response from conventional weapons effects.

Concrete wall perforated by bomb fragments

Bridge Assessment and Repair. Bridges are a major concern for the Army since it is responsible for the inspection, maintenance, and repair of over 3,000 bridges at Corps projects and Army installations worldwide. These bridges are susceptible to a wide variety of problems brought on by floods, scour, weathering, aging, and structural overload. WES provides technical support to the Corps of Engineers in all of these areas. Capabilities include in-depth structural inspection, scour assessment, underwater inspection, analytical load rating, on-site load testing, and guidance and specifications for repair. WES also provides technical training in bridge inspection, load rating, repair, and scour assessment.

Flood damaged bridge at Fort Richardson, Alaska

To deploy, project, and sustain forces, both in times of war and peace, the Army must be able to rapidly assess and repair any bridge on the road network over which troops and supplies must be moved. A major emphasis of the WES Bridge Assessment and Repair Work Package, begun in FY 96, is to develop an expert system, referred to as IBARR (Intelligent Bridge Assessment, Repair, and Retrofit), for the rapid assessment and repair of bridges. While providing analytical load ratings and repair and upgrade recommendations for well-defined bridges (i.e. those for which all structural details are known), IBARR will also contain knowledge-based inference routines for the assessment of inaccessible bridges, such as those behind enemy lines. It will also provide the capability to assess the residual capacity of damaged bridges and help determine repair requirements.



Fabrication of electrochromic devices capable of multiple color changes

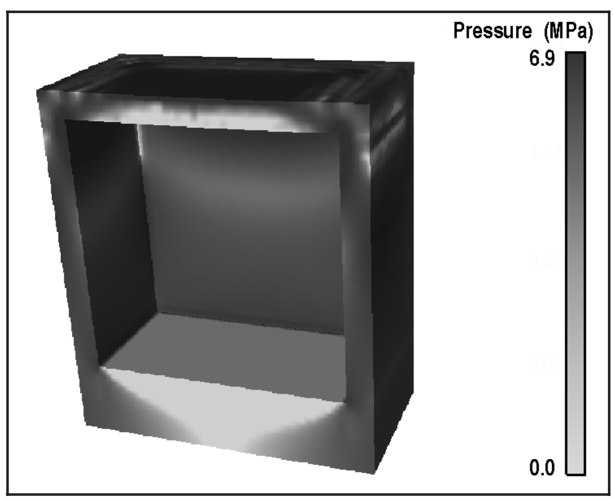
Camouflage, Concealment, and Deception. Basic research at WES has led to the creation of active visual camouflage materials that are capable of chameleon-like color changes. Experimental electrochromic devices, capable of multiple color changes, were created from a unique formulation of polymer blends and copolymers.

Because the appearance of color often varies from person to person, a spectrocolorimeter was used to document the color changes. Camouflage colors produced by these devices were measured in accordance with international standards for color description. This year the project produced two patent disclosures and received additional support from the Office of the Secretary of Defense.

Structure-Medium Interaction. A critical effort in the Structure Laboratory's mission is the development and validation of numerical simulation techniques and advanced nonlinear constitutive models. As part of our validation process, three structure-medium-interaction experiments were conducted in the WES Structural Dynamics Research Facility on identical 1:8-scale reinforced-concrete structures.

Each structure was buried in a sand backfill and then subjected to the ground-shock environment produced by detonation of a 0.9 to 2.7 kilogram explosive charge at a standoff distance of 0.7 meters. Detailed 3-D finite element simulations of these experiments were conducted with a large-strain Lagrangian wave propagation code that was enhanced by WES researchers with more robust constitutive models for geomaterials.

Ground-shock induced stresses and motions in the sand backfill surrounding the structures were calculated with a WES-implemented hybrid-elastic-plastic constitutive model that has been shown to accurately calculate ground shock stresses and motions in previous explosive events conducted in similar sand backfills. A new version of the Microplane (MP) model,



Calculated pressure contours in a reinforced-concrete structure subjected to a blast-induced dynamic loading a constitutive model jointly developed by researchers at WES and at Northwestern University, was used to simulate the concrete. The MP model accurately predicts the low-pressure brittle responses of concrete that are prevalent during the blast-induced dynamic loading of reinforced-concrete structures.

Comparisons of the calculated and measured results showed excellent quantitative agreement. These experiment-validated numerical tools will be used in the future to design cost-effective survivable structures to counter the threat from advances in weapons technology.

Explosives Safety Engineering. WES was the lead U.S. laboratory in a five-year cooperative research program with Korea to develop new design concepts for underground ammunition storage facilities. This program was completed in early FY 97. During the course of this program and related work, WES developed a significant technology base for the design of underground facilities to contain the blast effects of large explosions.

This technology was applied in a new project, funded by the Republic of Singapore, to design a large underground complex to store ammunition. The control of blast effects from an accidental explosion of ammunition was particularly crucial because of the high population density around the storage site.

An important component of the Singapore project was the prediction and analysis of ground-shock effects from an accidental explosion in an underground storage facility and the potential effect on nearby high-rise buildings. A WES team of specialists provided technical advice and assistance to engineers of Nanyang Technical University in Singapore for a series of experiments to calibrate the shock propagation properties of the native rock formations. This information was integrated with the magazine design to define the potential hazard distances for nearby structures.

Rock Penetration Research Program. Many critical military facilities are in underground rock formations to protect them from attack by air- delivered weapons. To defeat such facilities, weapons must penetrate the rock overlying the structure and detonate at a desired depth to impart the maximum amount of damage. The more robust weapons that can survive the penetration process generally have small explosive payloads which must detonate either within the target or very close to it to be effective. It is necessary to accurately predict a weapon's penetration performance (depth of penetration and penetration path) to select the optimum attack parameters.

However, the empirical models used to predict the penetrability of rock materials are not very reliable due to a limited rock penetration database. To address this problem, WES is performing a multi-year systematic investigation to obtain high quality rock penetration data to develop new and improved models to predict the performance of rock penetrating weapons.

In FY 97, WES performed a suite of high-velocity rock penetration experiments into a weathered granite rock in support of the

Mobile Ballistic Research System

Defense Special Weapons Agency's DIPOLE SAMSON Test Program. All of the experiments were conducted using WES's newly developed Mobile Ballistic Research System, which features a 152-mm powder gun, supporting instrumentation, and firing platform. Two penetrator configurations were evaluated at impact velocities up to 1,270 meters per second.

WES also coordinated a field subsurface exploration program and laboratory material property characterization program. The results from these investigations provided crucial geologic/geotechnical data needed to analyze the field penetration experiments.

Tunnel Target Vulnerability. In a cooperative effort with the Norwegian Defense Construction Service, WES designed, conducted, and analyzed the results of a series of explosive experiments against full-scale tunnel sections at a Norwegian site. The WES research was sponsored by the Defense Special Weapons Agency and the U.S. Air Force to evaluate modern weapon capabilities against hardened underground facilities. The detonations simulated air-to-surface weapon attacks against the tunnel entrances and internal detonations. WES engineers and technicians recorded blast and shock data from the experiments and will use this information to develop improved vulnerability assessment models.

Tunnel for joint WES/Norway vulnerability experiments

Half-Scale Cylindrical Charge Experiments. On June 25, 1996, an explosive-laden truck detonated next to Khobar Towers, which housed U.S. Air Force personnel in Dhahran, Saudi Arabia. The blast partially destroyed the building and caused 19 fatalities. The explosive charge was contained inside a cylindrically-shaped tank on the truck and is thought to have been covered by a liquid to prevent detection. The airblast and soil cratering produced by such a charge configuration is poorly understood, hindering both estimates of the size of the explosive charge used and predictions of damage levels from possible similar events in the future.

In support of the Federal Bureau of Investigation, the Defense Special Weapons Agency funded the Structures Laboratory to perform half-scale experiments simulating pertinent features (charge type, configuration, and geology) of the Dhahran bombing. The experiments were designed to obtain extensive airblast and cratering data and allowed the FBI to conduct damage and airblast correlations for "witness items," such as autos and signposts. The explosive charges were designed to bound the upper and lower limits of the estimated size of the Dhahran explosion and to investigate the tamping effect of liquid overlying the explosive. This was accomplished by detonating identically configured explosives, both with and without a covering layer of water.

The experiment series was successfully completed during the summer of 1997. Data gathered from the experiment are currently being used for comparison to the results of hydrocode calculations conducted at WES to simulate airblast and cratering from cylindrically shaped charges with and without water tamping. The data and calculational results will be used to formulate predictive methodologies for estimating the airblast field and crater produced by terrorist bombs similar to that used at Dhahran.

Post-shot view of site showing crater and damage to nearby truck

Test firing on a target with the SACON bullet barrier

Shock-Absorbing Concrete (SACON) for Military Training Ranges. WES is developing techniques for using foamed, fiber-reinforced concrete in bullet-trapping barriers on small-arms training ranges. The cells in the foamed concrete collapse as the bullet embeds itself in the barrier. No ricochets are produced and the bullet is held in a dry alkaline environment where metal leaching is minimized. The U.S. Military Academy at West Point, N.Y., and Fort Knox, Ky., are hosting demonstrations of this new technology.

SACON barriers keep the bullets out of the soil, minimize erosion, and reduce maintenance on the ranges. Techniques are being developed to recycle the bullet-impacted concrete after it has reached the end of its service life, so that new SACON can be made from the sand produced by crushing and sieving the used bullet barriers.

SACON can replace wooden and rubber barriers with non-flammable blocks that require no preservatives and are recyclable. In the future, SACON may become a common item on training ranges because of its ability to trap bullets that will reduce the amount of potentially toxic metal distributed over the range and possibly moving off-range and will help reduce the rate of soil erosion.

New Polymer Fiber and Fiber Delivery System. The structural load-carrying capacity of fiber-reinforced concrete (FRC), especially the ability of the fibers to carry tensile load after the concrete has cracked, has always been an issue in civil-engineering communities. While fibers do not have the tensile load-carrying capacity of steel reinforcing bars, they have proven themselves capable of reducing the width of shrinkage cracks and improving the flexural toughness and impact resistance of concrete in flexure, thereby improving the appearance and durability of the concrete.

The WES Structures Laboratory has been working with the 3M Company under a Cooperative Research and Development Agreement to develop a new polymer fiber and fiber delivery system for use by the construction industry as FRC for pavement, bridge-deck overlays, and ultrathin whitetopping applications. The polymer fiber itself is 50 millimeters long and 0.63 millimeters in diameter.

The fibers are bundled together by a tape system which is designed to dissolve in contact with water. The bundles are added to the concrete after the other components have been mixed together. The water in the concrete mixture dissolves the tape, and the agitation of the fiber bundles by the ingredients of the mixture as well as the blades of the mixer distributes the fibers throughout the concrete. This technique allows more fibers to be charged into each cubic meter of concrete. To achieve adequate fiber distribution, conventional polymer FRC is limited to approximately 1.8 kilograms per cubic meter of fiber. Using the 3M fiber-delivery system, 15 kilograms per cubic meter of fiber can be charged into the concrete with good fiber distribution.

Over 100 different mixtures with various types and volumes of fibers and proportions of fine aggregate, coarse aggregate, and various water to cement ratios were investigated by WES. The mixtures were measured for slump, unit weight, air content, and Vebe consistency. In addition, each mixture was evaluated for harshness and ease of finishing. Hardened properties of compressive and flexural strength, toughness, impact resistance, freezing and thawing resistance, drying shrinkage, and fatigue were also measured. The results of this matrix of mixtures provides a family of proportions which will work well in pavement and overlayment applications.

Recently, this fiber and its delivery system were demonstrated in an ultrathin whitetopping application on Interstate 20, one of the most heavily traveled interstate highways in the South. In Mississippi, much of this interstate is paved with asphalt. While asphalt is a good pavement material, the extremely hot temperatures in Mississippi, coupled with heavy axle loads of high truck traffic, have produced rutted and shoved pavement sections. These sections

A curing compound is sprayed on the 610-meter-long fiber-reinforced concrete whitetopping demonstration section on Interstate 20 are particularly dangerous after a rainstorm when the ruts become troughs filled with water trapped on the pavement surface.

At the demonstration site, the top 100 millimeters of asphalt pavement had been severely damaged by rutting. This damaged asphalt was milled from the remaining pavement and base, and the 3M polymer FRC whitetopping was placed in a single pass with a slipform paver. The concrete was proportioned for a 17-MPa compressive strength at 30 hours and contained 15 kilograms per cubic meter of fiber. The excellent toughness afforded by the high concentration of fibers in this mixture allowed the whitetopping to be placed in the 100-millimeter thickness and to require only a minimum of transverse control joints.

An inspection of the demonstration sections one month after placement revealed no visible deficiencies in the pavement. An evaluation with a falling-weight deflectometer indicated the pavement was much stiffer than prior to the whitetopping.

SUPERSCANNER. Currently, the only standard method of detecting delaminations in concrete bridge decks is the chain drag using American Society for Testing and Materials Standard D 4580, "Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding." As this method depends on someone having an "ear" for hearing the discriminating sound from a delamination, it is subjective. An objective method was needed to discern delaminations in bridge decks.

WES developed a high-frequency, high-resolution, ultrasonic pulse echo (UPE) system for this purpose. Numerous improvements were made on an UPE system developed at WES in the late 1980s. Although the former system excelled in resolution, it had limitations in a number of areas (speed of measurements, presentation of data, simplicity of operation, etc.). Important advancements were made in major areas, e.g., (1) new transducers with improved directivity, acoustic matching, and piezoelectric technology; (2) a "rolling pond" that increased the rate of measurements by 700 times; (3) interpretation of events in the composite signal that was improved by the development of a ray-based software model; (4) reduction of material noise (scattering) through the use of the Split-Spectrum Processing algorithm; and (5) presentation of results in the form of a B-scan graphic.

Also, a laboratory study of artificial neural networks showed that they can be used for signal recognition and hence for recognition of types of deterioration in the concrete. This permits the computer to replace the human expert once the expert's knowledge is entered into the computer through the use of EXPERT-system knowledge base. A library study of EXPERT systems showed that this software is suited to provide computer-aided guidance to help the operator conduct the complex measurement procedure.

The entire system has been named the SUPERSCANNER, the acronym for Scanned Ultrasonic Pulse-Echo Results by Site-Characterization of Concrete Using Artificial Neural Networks and Expert Reasoning. This new system has been demonstrated for its commercialization potential and competing with or replacing the chain drag method in the future. The WES prototype field system is available to perform evaluation services for various organizations.

Concrete Rheology Workability. The Federal Highway Administration and WES are working together to develop methods for measuring the flow properties of concrete. While the study has identified several commercial devices that use a variety of methods for measuring the rheology of concrete mixtures, none are capable of precise measurement over the broad range of flow characteristics seen in all of the varieties of concrete mixtures available to the construction and paving industries.

The ideal device would make precise measurements to allow early prediction of concrete placement problems at the work site and would make measurements rapidly and repeatably by inspectors with minimal training using only a few shovels full of concrete. Results should be available within minutes in a form that is readily understood by supervisors used to conventional slump-cone measurement methods. The device should be easy to calibrate, maintain and clean.

WES has fabricated four simple devices that will be evaluated. These devices include a vibrating slope, free orifice, moving object, and a rotating probe. The rheological data generated using these simple WES developed devices will be compared to data generated using the high-quality laboratory rheometer on similar concretes. Information generated from this program will aid in pioneering new standards and test methods for field measurement of concrete rheology.

Seismic Response of the Corps' Intake Towers. In an earthquake event, it is critical to prevent catastrophic failures of dams and subsequent sudden releases of reservoirs. If an earthen dam is damaged, lowering the water level will remove the hydrostatic pressure and help prevent failure. For most earthen dams, reservoir release is controlled through a reinforced-concrete intake tower. According to current analytical procedures, many of the Corps' intake towers may not survive specified ground motions. These lightly reinforced- concrete towers were designed using an older method that does not account for the dynamic characteristics of the structure.

Seventy-two intake towers designed and constructed before 1980 are in high seismic zones. Since retrofit of an existing tower is estimated at $5 million, savings could exceed $360 million if the inherent structural capacity of these existing intake towers is sufficient to remain functional when subjected to the design earthquake ground motions. A series of model experiments was designed by WES to understand the nonlinear response of lightly reinforced-concrete intake towers. These experiments will provide the necessary data for the development and validation of an evaluation procedure for these critical structures.

Two experiments of a 1:8-scale model of a typical tower configuration have been completed. The physical properties of the model were selected to be similar to the Lake Burnt Mills tower, a non-Corps structure, which is approximately one-half the size of a Corps intake tower. The experiments were conducted on the Structures Laboratory loading floor using the large-scale load frame.

The first experiment was a one-way excursion while the second was a cyclic load experiment. A vertical load was applied to the structure and held constant throughout the experiment to simulate the dead load. A horizontal load was applied by a deflection-controlled loader at a rate of 0.025 millimeters per second. These experiments were temporarily stopped six times to allow for a modal survey, measurements, and photography of the structure. The modal survey provided the dynamic characteristics of the model at different damage states. The dynamic characteristics include the modal shapes and corresponding dampening values and natural frequencies. This was the first time that dynamic characteristics of a structure have been obtained while it was undergoing damage.

Large-scale load frame

A displacement-based analysis method was developed based on the results of these experiments. This preliminary evaluation tool has already assisted in identifying six intake towers that may be removed from the list of intake towers with questionable dynamic capacity. This action alone could result in a $30 million saving.